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# Massive Neutron Stars with Hadron-Quark Transition Core —phenomenological approach by “3-window model”—

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**Abstract** By a new approach introducing a “3-window model” and constructing phenomenologically an equation of state for the hadron-quark (HQ) transition region, possible maximum mass of neutron stars (NSs) is discussed. It is found that neutron stars (NSs) with HQ transition core are able to have a mass exceeding  $2M_{\odot}$ , consistent with massive NSs recently observed.

**Key words** neutron stars—2-solar-mass—3-window model

## 1. INTRODUCTION

Recent observations of a two-solar-mass neutron star ( $2M_{\odot}$ -NS) <sup>[1,2]</sup> present a challenging problem how to accommodate a very stiff equation of state (EOS) responsible for such massive NSs. This problem is serious since every new exotic phase (e.g., meson condensation, hyperon (Y) mixing, quark (Q) matter) leads to a softening of EOS against the requirement from observations. For example, the Y-mixing softens the EOS dramatically and thereby the NS maximum mass ( $M_{\max}$ ) goes down to  $(1.1\text{--}1.2)M_{\odot}$  (“Hyperon Crisis”), clearly contradicting even the “minimal mass”  $1.44M_{\odot}$  observed for PSR1913+16 <sup>[3,4]</sup>.

The aim of this paper is to discuss how NSs could be massive, by introducing a quark degrees of freedom. Our strategy for the approach is to divide the EOS into three density ( $\rho$ ) regime i.e., pure hadronic matter EOS (H-EOS,  $\rho \leq \rho_H$ ), hadron-quark transition matter EOS (HQ-EOS,  $\rho_H \leq \rho \leq \rho_Q$ ) and pure quark matter EOS (Q-EOS,  $\rho \geq \rho_Q$ ), which we call “3-window model” <sup>[5–9]</sup>. This is motivated by the following considerations: Pure hadron-matter EOS calculated from point-like hadrons plus their interactions loses the validity with increasing  $\rho$ , primarily because baryons have a finite size composed of quarks (and

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gluons) and deconfinement effects come into play. Also pure Q-matter EOS gets uncertain with decreasing  $\rho$  because strong correlations among quarks would develop and confinement effects would participate. Our basic idea is to supplement the very poorly known HQ-EOS relevant to a confinement-deconfinement transition, by sandwiching it in between the relatively certain H-EOS at lower density side and Q-EOS at higher density side. We stress that our new approach to the H-Q transition is not restricted by a conventional Gibbs or Maxwell condition which necessarily leads to a softening of EOS.

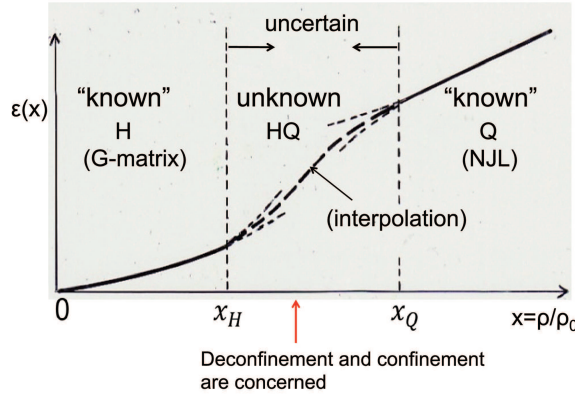


Fig. 1 Schematic illustration of “3-window model”. Energy density  $\epsilon$  versus  $\rho$ .

## 2. CONSTRUCTION OF EOS

We use the H-EOS from a G-matrix-based effective interaction approach applied to neutron-star matter composed of  $N(\equiv n, p)$ ,  $Y(\equiv \Lambda, \Sigma^-)$  and leptons  $\{e^-, \mu^-\}$  being in  $\beta$ -equilibrium and charge neutrality<sup>[4]</sup>. The H-EOS is designed to satisfy the saturation properties of symmetric nuclear matter and gives nuclear incompressibility of  $\kappa = 250$  MeV consistent with experiments. As for the Q-EOS, we use that from an effective theory of QCD, namely, the (2+1)-flavor NJL model with the Hatsuda-Kunihiro parameter set, where Q-matter composed of  $\{u, d, s\}$  quarks and leptons  $\{e^-, \mu^-\}$  are in a charge neutral and  $\beta$ -equilibrated system<sup>[6,7]</sup>. In the model Lagrangian, we include a phenomenological vector-type interaction with the strength  $g_v$  which leads to an universal flavor-independent repulsion among quarks, contributing to a stiffening of the Q-EOS.

Concerning the HQ-EOS, we obtain it by a phenomenological interpolation taking the interpolation function  $\epsilon_{HQ}(\rho)$  of a form of 5-th degree polynomial with 6-parameters. The 6-parameters are determined by the 6-conditions that the energy density  $\epsilon(\rho)$ , the pressure  $p(\rho)(= \rho^2 \partial(\epsilon/\rho)/\partial\rho)$  and the sound velocity  $v_s(\rho)(= c\sqrt{\partial p/\partial\epsilon})$  are coincide with each other at two boundaries ( $\rho = \rho_H$  and  $\rho = \rho_Q$ ). The  $\epsilon_{HQ}(\rho)$  is restricted by the conditions,  $p \geq 0$ ,

$\partial p / \partial \rho \geq 0$  and  $v_s \leq c$ .

**Table 1** Some results of maximum mass ( $M_{max}$ ) neutron stars.

	$g_v/G_S = 0$		$g_v/G_S = 0.5$	
$(x_H, x_Q)$	(1.5, 11)	(1.5, 8.5)	(1.5, 11)	(2, 11)
$M_{max}/M_\odot$	1.79	2.36	2.21	2.20
$R(\text{km})$	10.2	11.4	10.8	10.4
$\rho_c/\rho_0$	7.25	5.32	6.04	6.33

$g_v(G_S)$  denotes the strength of a vector (scalar) interaction.  $R(\rho_c)$  is the radius (central density) of NSs.

### 3. RESULTS AND CONCLUDING REMARKS

We have studied how massive could be the hybrid stars with quark degrees of freedom, by phenomenologically constructing the EOS with hadron-quark transition in a new approach characterized by “3-window model”. Some numerical results are shown in Table 1 where  $R(\rho_c)$  is the radius (central density). It is found that NSs with a HQ transition core have a potentiality to generate massive NSs, e.g., with  $M = (2.2 - 2.4)M_\odot$ , as far as a quark degrees of freedom sets in at rather low-density  $((1.5 - 2)\rho_0$ , with  $\rho_0 = 0.17/\text{fm}^3$  being the nuclear density) due to the percolation of quarks in hadronic matter<sup>[10]</sup> and the EOS of quark matter is stiff. The results from the present approach confirm those of our preceding works performed from a HQ crossover picture<sup>[6,7]</sup>.

Finally, we want to remark that the possible candidates to resolve the “Hyperon Crisis” problem are the “universal 3-body force” when a purely hadronic scheme is taken, as shown previously<sup>[11]</sup>, and the HQ transition occurring in NS cores when {hadron+quark} scheme is considered.

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